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TECHNOLOGICAL PROBLEMS ANITICIPATED IN THE APPLICATION OF FUSION REACTORS TO SPACE PROPULSION AND POWER GENERATION

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TECHNICAL PAPER prepared for presentation at
Fifth Intersociety Energy Conversion Engineering Conference
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

Mission and system studies have shown that fusion reactors potentially may be the most attractive energy source for space power and propulsion systems. The methods by which fusion reactors may be applied to space missions are discussed. The problems posed by conversion of the thermal energy of the reacting plasma to electrical power and/or an exhaust jet are considered. Conceptual approaches to space applications are described, and their implications for research and development in the 1970's are reviewed.

Recent analytical and experimental studies conducted at the NASA Lewis Research Center are reviewed, and their significance for the future direction of space-related fusion research are discussed.

Introduction

Very encouraging progress over the past 5 years has been reported in the field of controlled fusion research (Ref. 1). Several basic problems that were thought to stand in the way of achieving energy densities and confinement times of thermonuclear interest have been circumvented or overcome. Some of the highlights of this progress include the reporting of radial diffusion rates substantially slower than the Bohm value (Refs. 2 and 3); macroscopic stability of toroidal plasmas (Refs. 2 to 4); successful demonstration of techniques for the feedback stabilization of a broad class of macroscopic instabilities, which are now available should such instabilities arise (Refs. 5 and 6); and the demonstration that neither an energy density gradient (the free energy reservoir responsible for the hypothetical "universal" instability) nor small-scale fluctuations of the plasma properties necessarily imply a radial diffusion rate in excess of the classical value (Refs. 2 to 4).

In this climate of progress, it is appropriate to review and project space-related fusion research for the decade of the 1970's. The promise of fusion reactors for space power and propulsion systems was early recognized (Refs. 7 and 8) and has recently been discussed and compared with other systems by Moeckel (Ref. 9). These fusion systems would be assembled in earth orbit; operate only in deep space; would be used for round-trip manned missions to the planets or their satellites; and would accomplish their missions in times much shorter than those anticipated for other propulsion systems. A spaceship containing such a fusion propulsion system would have a typical initial mass of 10^6 kilograms, and would be appropriate to a period when large payloads must be moved to and from the planets.

Potential advantages of fusion systems include the following factors:

(a) For a given payload mass, the initial mass in earth orbit and round trip mission time are much smaller for fusion systems than for chemical systems, because the former can operate at the optimum exhaust velocity for the mission.

(b) The initial mass in earth orbit and round trip mission time, for a fixed payload, is significantly smaller for fusion systems than for fission rockets or fission-electric systems. This comes about from the ability of fusion systems to operate at the optimum exhaust velocity for the mission, the possibility of direct conversion of plasma enthalpy to thrust or electrical power, and the reduced mass of moderating and shielding material if there is no requirement for neutron economy.

(c) If either the D-He^3 or the D-D reaction can be harnessed for space applications, the fuel should be inexpensive enough to exhaust directly into space along with the propellant. Tritium and fissionable fuels will probably be too scarce or expensive to allow the unused fuel to be lost to space.

System Configuration

In order to establish a conceptual framework for further discussion, schematics of various possible applications of fusion reactors to space propulsion will be discussed. The first, and least attractive system, is that shown in Fig. 1, in which the fusion reactor is used as a source of heat energy for the generation of electrical power. The electrical power is converted to thrust by an MPD thruster or by an ion engine. This concept has many of the drawbacks of fission-electric systems, including a relatively high mass/power ratio and a Carnot efficiency limited by the melting point of solid components of the reactor-generator system.

A somewhat simpler and more elegant system is shown in Fig. 2, in which the charged reaction products are converted directly into electrical power in a manner proposed by Post (Ref. 10). In this system, the charged reaction products that escape from the confining magnetic field impinge on collecting electrodes, thus generating electrical power directly.

The simplest and most elegant application of fusion reactors is shown schematically in Fig. 2, in which the escaping plasma is mixed with additional propellant and exhausted in a magnetic nozzle to provide thrust. This arrangement constitutes a direct fusion rocket, similar in principle to a chemical rocket, but utilizing nuclear rather than chemical combustion.

Space Systems Versus Ground-Based Systems

Problems Common to Both

Because it is not our purpose to review the problems of fusion research per se, the problems common to both space and ground-based fusion reactors will be listed with brief comments. Some of the common problems of basic physics include the following:

(a) Injection of plasma into confinement volume (Ref. 11)

(b) Stability of plasma on microscopic and macroscopic scales

(c) Heating of plasma to thermonuclear conditions

(d) Net energy production from reactor

(e) Minimizing radial diffusion of plasma

(f) Minimizing cyclotron radiation from plasma

The problems of radial diffusion and stability of plasma appear on the way to solution as a result of recent research (Refs. 1, 4, and 5). The problems associated with plasma heating and maximizing the fusion reaction rate will probably dominate fusion research in the 1970's, just as stability and radial diffusion have been the focus of research in the 1960's.

Some of the engineering problem areas common to space and ground-based fusion reactors include the following:

(a) Further development of superconducting magnet technology

(b) Development of long-lived first surface material

(c) Removing heat flux from first surface and protective blanket for superconducting coils

(d) Develop a suitable blanket to shield superconducting magnets from neutron flux

(e) Conversion of plasma enthalpy to electrical power for on-board and propulsion system use

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(f) Radiation damage of wall materials by neutron flux

Problems More Important to Ground-Based Fusion Reactors

In general, developing a successful fusion reactor for space applications will be more difficult than a similar ground-based reactor for electrical power generation (Ref. 12). However, some problems of ground-based fusion reactors may be simplified or eliminated in space applications. These problems include the following:

(a) Safety considerations alone will require the complete shielding and absorption of the flux of radiant energy and neutrons from ground-based fusion reactors. In addition, neutron economy will be required for tritium breeding in such reactors if the D-T reaction proves to be the only feasible system. If the D-D or D-He^3 reactions prove to be capable of producing a net power output, it may be unnecessary in space applications to conserve either the neutrons or their energy. The design of the superconducting coils and shields should then be such as to maximize the fraction of neutrons that escape freely to space. If the cyclotron radiation turns out to be unimportant to the energy balance of the plasma, this too can be reflected from the coil structure and channeled to space. If either the neutrons or the radiant energy is reflected to space, it will be possible to reduce massive equipment otherwise required to absorb and re-radiate the energy flux from these sources.

(b) The maintenance of a vacuum environment for the reacting plasma will be a major item of capital costs and a constant threat to the uninterrupted operation of ground-based fusion reactors. Since presently envisioned fusion propulsion systems will be limited to orbit-to-orbit missions because of their low thrust/mass ratio, a vacuum environment will be available at all times.

Problems More Important to Space Applications

Many of the problems of basic physics stem from the fact that the D-T reaction does not appear promising for space applications. Currently envisioned ground-based fusion reactors are expected to operate on the D-T reaction, and simply produce a net power output (Refs. 1 and 6). Such reactors will, in all probability, have massive and complicated subsystems for injecting energetic plasma, and for the breeding and recovery of tritium. These subsystems tend to rule out the D-T reaction for space applications.

(a) In order to eliminate systems for the injection of energetic plasma, space-borne fusion reactors must be self-sustaining as well as capable of producing net power, i.e., the charged reaction products must be capable of heating neutral fuel injected at ordinary temperatures to temperatures high enough to produce at least one further fusion reaction.

(b) The neutrons produced in fusion reactions will not contribute directly to heating the reacting plasma, while the slowing-down of charged reaction products will. The energy of the neutrons will be either lost directly to space, or must be absorbed by the structure and re-radiated to space by cooling systems. It is therefore desirable to minimize the production of neutrons from the reaction, and maximize that of charged particles. The D-T reaction is unsatisfactory from this standpoint, since about 80 percent of the reaction energy is carried away by neutrons. Although the D-He^3 reaction will produce some neutrons from concurrent D-D reactions, the neutron flux will be many times smaller than from either D-D alone or D-T. In addition, a further reduction can be expected if one alters the reactant proportion from 50 percent each to an excess of He^3.

(c) The contemplation of the D-He^3 reaction for space applications suggests other problems. First is the probability of higher reaction temperatures than would be needed for the ground-based systems. Englert (Ref. 13) has shown that this in turn will cause an altered balance in the system energetics - the ratio of ion to electron temperature, the energy flow from the reaction products to ions and electrons, the buildup of alpha particles in the reaction volume, and the intensity of bremsstrahlung and synchrotron radiation. All these factors need a more careful evaluation than has yet been given them.

(d) If direct conversion to electrical energy or thrust, illustrated in Figs. 2 and 3, is utilized, a method must be developed to control the ions escaping from the plasma. Their velocity vectors must be made unidirectional through manipulation by electric and magnetic fields.

(e) The charged reaction products lost from a self-sustaining D-D or D-He^3 reactor will consist of these species, with a small admixture of tritium, protons, and He^4. In a self-sustaining fusion reactor, the charged reaction products would be at the operating temperature of the reactor, in the range of from 40 to 100 keV. The velocities of these species in this range of kinetic temperatures is about a factor of 10 higher than the optimum propellant velocity required for interplanetary missions (Refs. 7, 8, 9, and 13). Mixing of the beam of escaping charged particles with a substantial quantity of propellant gas is therefore required for optimum performance. Studies of this propellant mixing problem (Ref. 14) have shown that propellant injected into the beam of escaping ions can raise the average momentum of the exhaust jet to the desired values. This mixing problem is a crucial one for fusion rockets, and further experimental studies of relevant cross sections and the entrainment of neutral gas by plasma beams appears desirable.

(f) A suitable heat-transfer method will have to be developed to carry heat away from the superconducting coil shields, and for use in the generation of electrical power for on-board and propulsion system needs. Problems of this nature are considered in the magnetocaloric power generating cycle to be discussed below.

Many of the engineering problems associated with space-borne fusion reactors are similar in kind to those associated with space applications of fission rockets and fission-electric propulsion systems. Many of these common problems are under study for application to fission systems, and include the following areas:

(a) Development of lightweight components throughout

(b) Development of energy conversion system for electrical power needs

(c) Development of heat transfer and radiation system for waste heat

Other engineering problems are more or less unique to space-borne fusion reactors, and would have to be approached ab initio for this application. Such problems include the following:

(d) The development of a lightweight liquid helium refrigerator to extract and reject heat leaking into the superconducting coils.

(e) Special consideration must be given to cryogenic cooling in a near zero gravity environment.

(f) A lightweight system is needed to provide a repeated startup capability in space. Such a system may have to provide electrical power comparable to the steady-state output of the fusion reactor - at least several hundred megawatts - for a period of time comparable to the individual ion confinement time, on the order of 1 second. One possible concept for the source of such start-up power is a chemically powered MHD generator, which produces a large pulse of electrical power over the duration during which a charge of chemical propellant burns. Such systems need not be very massive. For example, the combustion of only 100 kilograms of hydrogen and oxygen would produce 1000 megawatt-seconds of energy. Converting such energy into a form usable for startup will, of course, add mass to the system.

Concepts for Space Applications of Fusion Reactors

The problems discussed above, associated with space applications of fusion reactors, may be approached in a variety of ways. We will discuss some of these approaches.

The Direct Production of Thrust from Fusion Reactors

Direct conversion of the reacting plasma energy to thrust should involve the minimum propulsion system mass to power ratio, and is therefore most desirable. Such direct conversion might be accomplished in open-ended mirror systems by one of the two arrangements shown in Figs. 4 and 5. Figure 4 illustrates the use of an asymmetrical magnetic mirror, in which one mirror is much stronger than the other. The charged particles would flow preferentially out the weak mirror, and through a guide field where the departing plasma is mixed with neutral propellant gas to obtain the optimum exhaust velocity. The plasma escaping through the stronger mirror could be used for direct conversion to electrical power for on-board needs. In Fig. 5 is shown a symmetrical magnetic mirror machine, in which the plasma leaking out both ends is turned through 90^{o} by a magnetic guide field, in which the propellant mixing takes place.

The direct production of thrust from toroidal geometries presents additional problems, since there is no single hole in the magnetic field through which the bulk of the plasma will be lost. Space-borne fusion reactors will require the simplest possible magnetic field geometry, in order to conserve mass and reduce to an absolute minimum the thermal energy intercepted by the reactor structure. The relatively complicated conductor configurations used to stabilize present-day toroidal plasmas are undesirable. An attractive possibility for space applications is the "bumpy torus" geometry, originally proposed by Gibson et al. (Ref. 15). This consists of simple current loops placed in a toroidal array, and allows significant apertures for escape of neutrons and radiant energy to space. If stabilization of macroscopic plasma instabilities proves necessary, this might be accomplished by dynamic or feedback stabilization.

The plasma will escape from the bumpy torus geometry by radial diffusion. This radially escaping flux can be skimmed off the outermost drift surfaces and manipulated into a unidirectional beam by a device similar to the Princeton "divertor" (Ref. 16), or by a modified, time-reversed version of the electron injection scheme used for entropy trapping in the original bumpy torus apparatus (Ref. 17). One conceptual approach to the problem is shown schematically in Fig. 6. The escaping plasma in this unidirectional beam can be mixed with additional propellant gas to obtain the optimum exhaust velocity.

Novel Systems for Cooling and Generation of Electrical Power

In space-borne fusion reactors, it will be necessary to remove large amounts of heat from the first surface and shielding blankets which surround the superconducting coils, and transfer this heat energy to a space radiator and/or to the propellant. Unconventional systems for power generation and cooling merit investigation. Promising concepts include heat pipes, direct generation of electrical power in the manner proposed by Post (Ref. 10), and the use of a magnetocaloric cycle with the cooling fluid (Ref. 18).

A magnetofluid is ferromagnetic at ordinary temperatures and is strongly attracted to regions of high magnetic field. This magnetic attraction is illustrated in Fig. 7, which shows a dish of ferrofluid surrounding a wire. When a current flows, the magnetic field attracts the ferrofluid up the surface of the wire. If the magnetofluid is heated to its Curie temperature while in a strong magnetic field, the magnetic field no longer attracts it, and a pressure head results. This pressure head can be used to pump the fluid between a hot region in a strong magnetic field and a radiator in a weaker magnetic field, as shown in Fig. 8. If the magnetofluid is a liquid metal, it can be made to flow across the magnetic field and generate electrical power. Successful magnetofluids based on finely divided iron suspended in kerosene have been demonstrated (Refs. 19 and 20), but liquid metal magnetofluids usable in fusion reactor applications remain to be developed.

Shielding of Superconductive Coils

Studies have been made of the shielding requirements of superconductive coils in ground-based fusion reactors based on the D-T reaction (Ref. 21). These studies show that blanket thicknesses of at least 1 meter will be required, most of this for the tritium breeder blanket. As previously stated, the enormous mass of such blankets, and the necessity of surrounding the entire plasma to get favorable tritium breeding ratios, virtually rules out the D-T reaction for space applications. If the D-D or D-He^3 reaction were used, the coils could be surrounded by a neutron reflector, like that shown in Fig. 9. This figure represents schematically a two-coil sector of a twelve-coil bumpy torus magnetic field. The basic design philosophy of such an arrangement would be to reflect as much radiant energy and as many neutrons as possible into space, so that their thermal energy will not have to be dealt with. Most of the neutrons that get past the reflecting material would be moderated and absorbed before they could reach the liquid helium environment around the coils. The thermal energy appearing in the shield would be removed by the magnetocaloric cycle discussed above, or by conventional heat transfer systems. The first surface would have a high reflectivity, in order to reflect the longer wavelength radiant energy into space as well. Such a reflecting shield should be much lighter than the tritium breeder shields required for ground-based fusion reactors. Even with shields and baffles, the heat leak to the superconductive coils must be removed. This may be accomplished if the liquid hydrogen (or deuterium) propellant is available as a heat sink for the refrigerator (Ref. 13). The refrigerator mass may become prohibitive if the heat flux carried by the neutrons is too large, or if not enough propellant is available as a heat sink.

Status of Space-Related Fusion Research

A modest effort is underway within NASA to identify and explore crucial problems, with long lead times, which stand in the way of space applications of fusion power. This work at present includes systems and mission studies to identify the potential of fusion power for space applications; development of superconducting magnet technology required for fusion and other advanced space energy conversion systems; and two experimental approaches to the problem of plasma heating and confinement (Ref. 22).

Systems and Mission Studies of Fusion Propulsion

At the present stage of development of controlled fusion, systems studies for fusion rockets necessarily rest on a shaky foundation of assumptions. Such studies are useful in two ways. First, unless reasonable assumptions result in a forecast of very substantial gains over alternative systems, one is deterred from what would probably be an unprofitable line of investigation. Second, in the analysis one can identify which assumptions are most critical to the outcome, thus showing which additional information will most improve the reliability of the results.

A system study of a fusion rocket has been performed by Englert (Refs. 13 and 14), who assumed an open magnetic configuration and included calculations of methods of dealing with the heat load to the liquid-helium temperature superconductive magnets. Later analysis (Ref. 14) of the mixing process, energetic escaping plasma mixing with hydrogen propellant, showed the feasibility of direct acceleration of the propellant inside a magnetic nozzle. System specific mass approaching 1 kilogram per kilowatt of jet power was obtained, at specific impulses of the order of a few thousand seconds. Using such values for the system, Moeckel (Refs. 9 and 22) obtained significant improvement over other propulsion systems in orbit-to-orbit round trip mission times to other planets. Results for a Mars mission are shown on Fig. 10. Even more favorable results were reported (Refs. 9 and 22) for missions to the outer planets.

Superconductive Magnet Technology

Several advanced propulsion systems other than fusion reactors will require the high magnetic fields and low power consumption afforded by superconductive coils. NASA has accordingly supported the development of superconductive magnet technology, with the very encouraging results reported by some of our colleagues (Refs. 23 and 24). One of the results of this work is a set of four superconductive coils that together will achieve 5.9 Tesla on the axis of its approximately 51 cm diameter bore, when operated at the lambda point of liquid helium. These magnetic field characteristics are within a factor of 2 in magnetic field strength, and within a factor of 2 to 5 in diameter, of those envisioned for eventual space-borne fusion reactors. This work has also produced a 15 cm diameter superconductive coil that will produce 15 Tesla on its axis (Refs. 22 to 24). No problems have arisen in the course of this work which would imply any particular roadblocks in the way of scaling much magnets up to the size required for fusion reactors. However, current practice in these superconductive magnets involves the use of substantial proportions of normal conductors paralleling the superconductors for stabilization. Thus the effective current density is much less than would be anticipated for the superconductor alone. Other methods for minimizing the mass of such stabilizing material are being studied (Ref. 22). Current densities greater than 10^5 amps/cm^2 are desirable for space applications.

The first superconductive magnet facility to be used for plasma physics and controlled fusion research went into service at the NASA Lewis Research Center in December, 1964 (Ref. 25). A photograph of this facility is shown in Fig. 11. It is a magnetic mirror apparatus, each coil of which can generate up to 2.5 Tesla on the axis of its 18 cm diameter bore. This magnet facility has completed 5 years of satisfactory service without degradation of coil performance.

Modified Penning Discharge

The modified Penning discharge is one of two experimental approaches to fusion-related plasma problems at the NASA Lewis Research Center. The plasma produced in this discharge is shown in Fig. 12. The vertical element in the center is the anode ring, which is operated at a positive potential of several tens of kilovolts. The energy of the deuterium ions escaping from the magnetic mirrors was studied as a function of the anode voltage and background pressure, with the result shown on Fig. 13 (Ref. 28). The ion kinetic temperature is directly proportional to the anode voltage for each pressure, up to the limit of the power supply used, suggesting that ions of higher energies can be obtained by going to a sufficiently high anode voltage. The ion velocity distribution was found to be Maxwellian, and the electron energies were much lower than those of the ions. Both of these characteristics are very desirable in fusion applications; the Maxwellianization of the ion velocity distribution implies one less free energy reservoir to drive macroscopic and microscopic plasma instabilities; and it is desirable to dump the power supply energy into the ions rather than the electrons.

The best temperatures, densities, and confinement times observed simultaneously in this experiment thus far are as follows:

Ion kinetic temperature	5 keV
Electron kinetic temperature	200 eV
Plasma number density	$2\times10^{16}/m^3$
Ion confinement time	27 microsec

The ion and electron energies are quite promising, but the densities and confinement times are low as a consequence of end losses out the magnetic mirrors. These losses can be eliminated, and the density and confinement times increased, by using the modified Penning discharge in a bumpy torus configuration like that shown in Fig. 14. Such a magnetic field configuration, with twelve 30 Tesla superconducting coils each with an inside diameter of 17 cm, is under construction for future use in this experiment.

Ion Cyclotron Resonance Heating

Another example of high temperature plasma physics research at NASA Lewis Research Center is the ion cyclotron resonance heating (ICRH) program (Refs. 22 and 28). This heating scheme uses radiofrequency power to heat plasma ions in a steady-state manner. A schematic of the ICRH experiment is shown in Fig. 15(a). A specially designed radiofrequency coil, shown in Fig. 15(b) is located at the center of the system. This coil generates ion cyclotron waves which propagate axially away from the center section to the ends of the discharge chamber. The confining magnetic field near the ends is adjusted so that the ion gyrofrequency of the plasma is equal to the ion cyclotron wave frequency. Under this resonant condition, the ions rapidly absorb energy from the r-f electric fields of the ion cyclotron wave.

The objectives of this research are: (1) to assess the potential of the ICRH process for achieving fusion conditions; and (2) to develop a good research tool that produces a hot, dense plasma which can be used to study some of the basic problems in fusion research. Both theory and experiment indicate that r-f power can be efficiently coupled to ion cyclotron waves in the plasma. The conversion of ion cyclotron wave energy into ion energy is presently under investigation in this experiment.

While operating in the steady-state, ion temperatures of 500 eV have been achieved in a plasma of 10^{18} m^{-3} density (Ref. 29). A graph of ion energy as a function of axial position, taken with diamagnetic loops, is shown in Fig. 16. Limitations to this heating scheme have become apparent. First, the coupling efficiency from the coil to ion cyclotron waves is reduced as the plasma ion temperature increases (Ref. 20). Second, only a small percentage of the power coupled into ion cyclotron waves is at present converted into ion thermal energy. Theoretical explanations for these limitations have been suggested, and ways of avoiding them are under investigation. These limitations and those of other heating methods may imply that more than one heating method will be necessary to raise plasma to thermonuclear conditions. In spite of these limitations, ion cyclotron resonance heating has produced a hot, dense, steady-state plasma which is, in itself, a valuable fusion research tool. Ion cyclotron resonance heating may be useful for reactor startup in space, even though, as previously noted, any continuous use of large amounts of power seems nonfeasible.

A major objective of our future plans is to apply ICRH to various open-ended magnetic wells. One purpose of these tests will be to study experimentally the generation, propagation, and damping of waves in the more complex magnetic fields of these wells. Another reason for applying ion cyclotron resonance heating to open ended magnetic wells is to perform plasma stability studies in the regime of high ion density and temperature. Theory predicts that the so-called velocity space instabilities will occur at high densities in mirror machines. An experimental study is planned for a superconductive magnetic mirror apparatus, shown in Fig. 17, which will be capable of producing magnetic fields up to 8 Tesla over a 51 cm bore.

Discussion and Conclusions

Many of the foreseeable problems associated with space and ground-based applications of fusion reactors appear to be common to the two applications, while some are unique to the respective application. A similar degree of commonality and uniqueness seems to hold for existing developmental programs leading to space and ground-based applications of fission reactors.

If self-sustaining fusion reactors based on the D-He^3 (or possibly the D-D) reaction can be achieved, it is possible that fusion reactors will see their first large scale applications in space, rather than for ground-based electrical power generation. Studies have shown that fusion reactors may be marginally competitive economically with other projected power generating systems (such as advanced fast breeder reactors) on the ground (Refs. 6 and 12), while mission analyses indicate that fusion reactors may be much superior to other competing space power and propulsion systems (Ref. 9).

Some of the major research areas related to space applications that should receive attention are: (1) a more detailed study of the D-He^3 reaction characteristics, (2) the study of energy transport at the higher plasma temperatures involved, (3) systems studies of a D-D reactor, with loss of neutrons to space, (4) experimental and theoretical work on the conversion of the plasma energy to power or thrust, (5) studies of neutron and radiation shielding methods for superconducting coil protection, (6) development of lightweight, high current density superconducting magnets, lightweight cryoplants, and associated systems components, and (7) development of a liquid metal ferrofluid suitable for space applications of magnetocaloric pumping and power generation. Work is also needed on methods of collecting the radially diffusing plasma from toroidal systems, and converting it into a unidirectional exhaust beam. One of the most important unknowns, the space-restart system, cannot be adequately specified until controlled fusion has been achieved.

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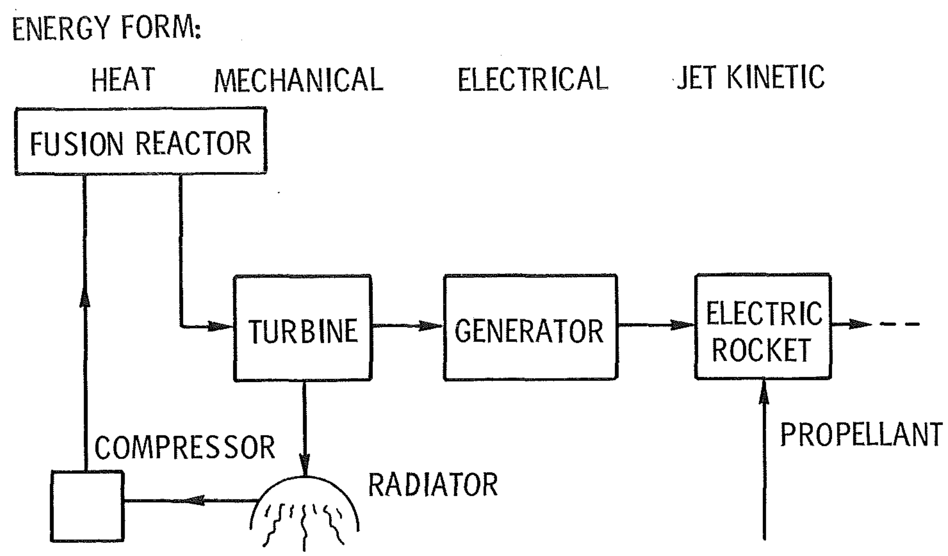

Figure 1. - Fusion-powered electric propulsion system with heat cycle.

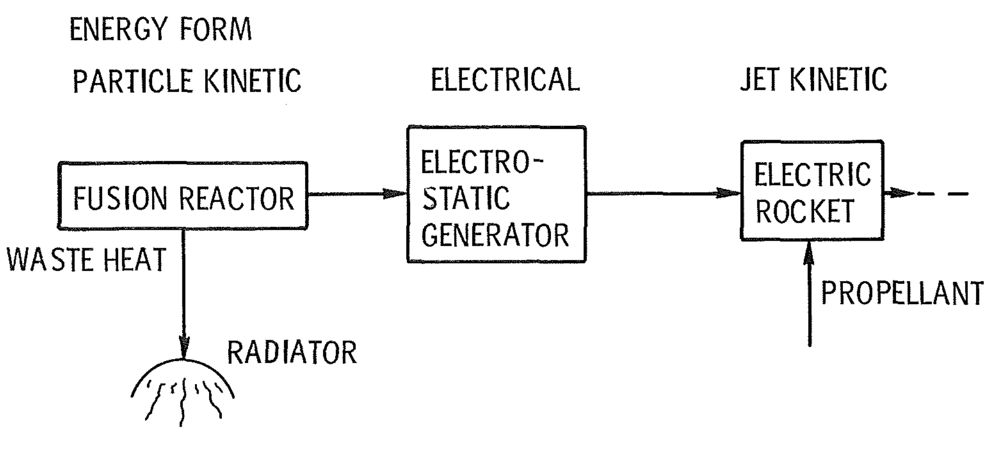

Figure 2. - Fusion-powered electric propulsion system with direct conversion.

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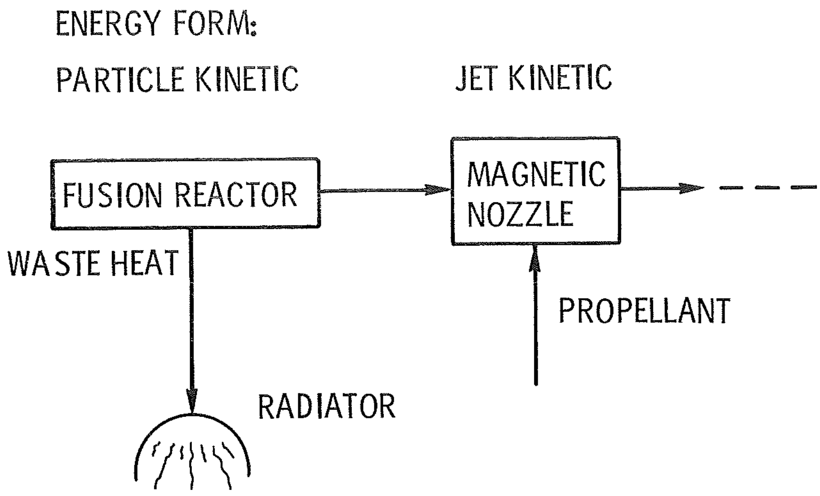

Figure 3. - Fusion rocket system; hot plasma efflux accelerates propellant in a magnetic nozzle.

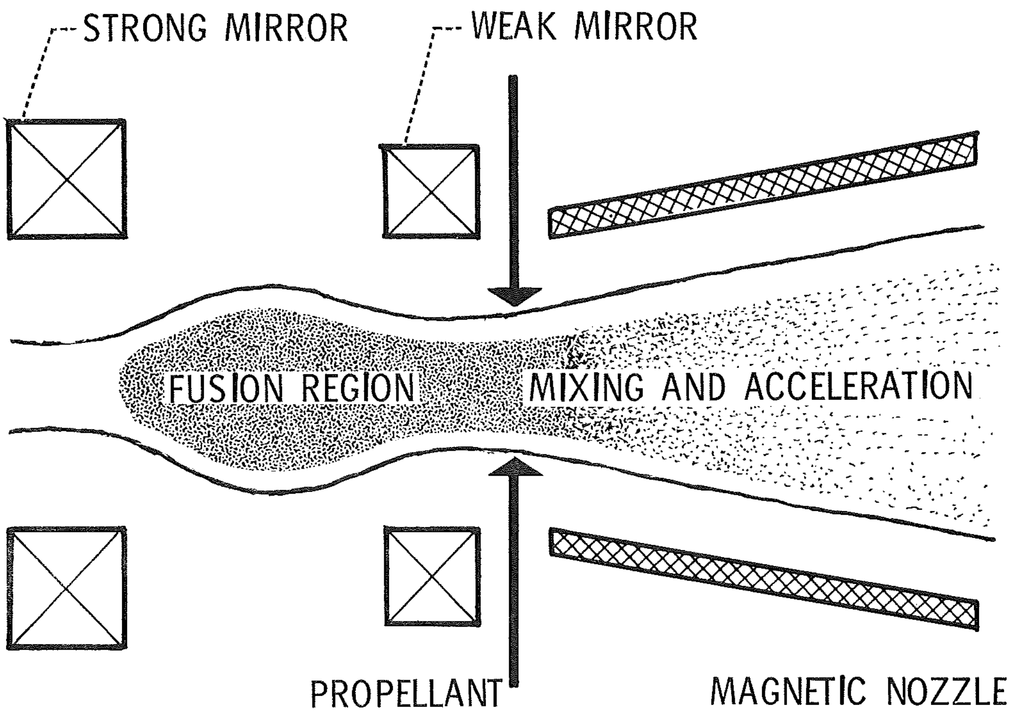

Figure 4. - System for direct production of thrust from open magnetic configuration. Single-ended system; predominant particle loss occurs through weaker mirror.

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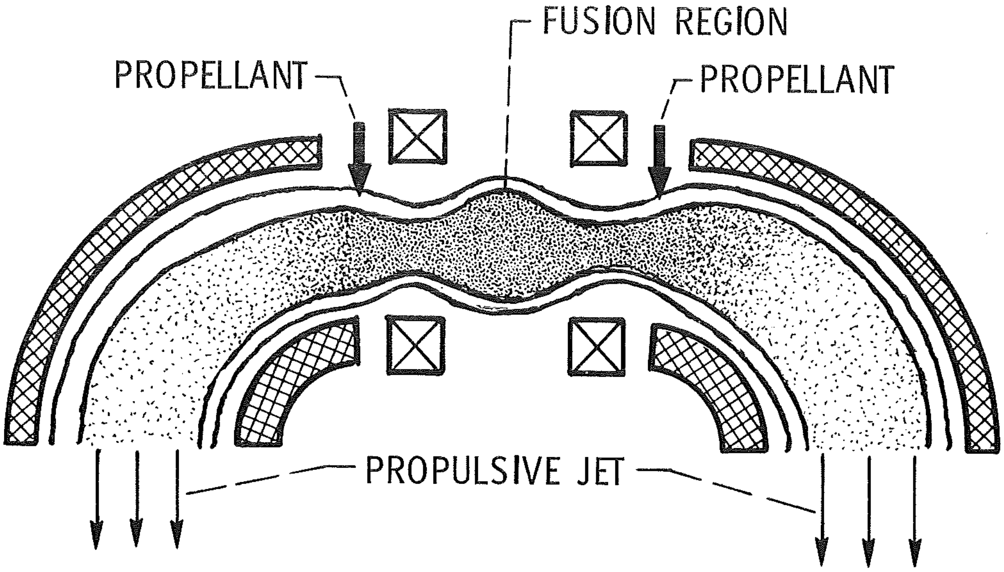

Figure 5. - Double-ended system for direct production of thrust. Losses through both mirrors used to produce thrust.

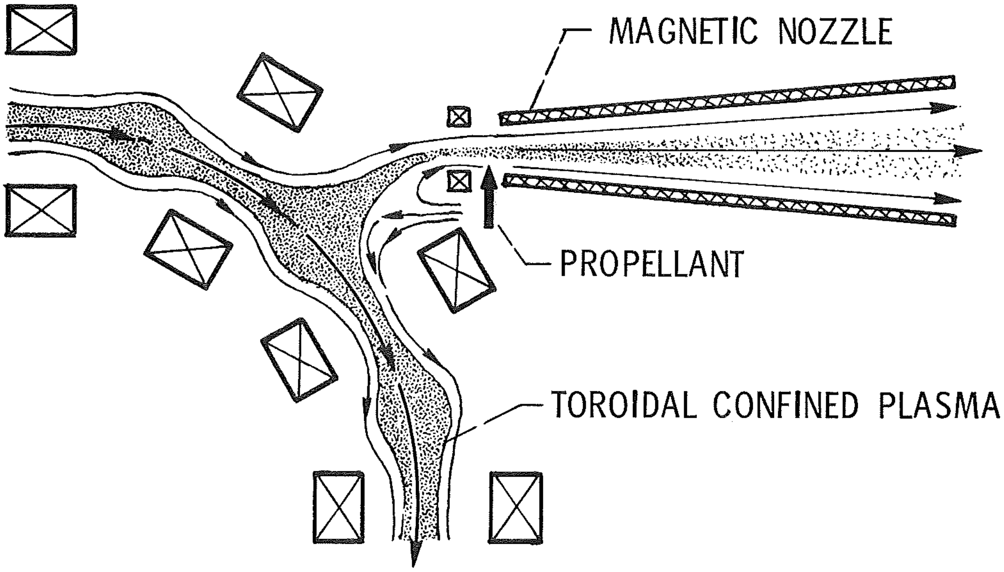

Figure 6. - System for direct production of thrust from closed magnetic configuration.

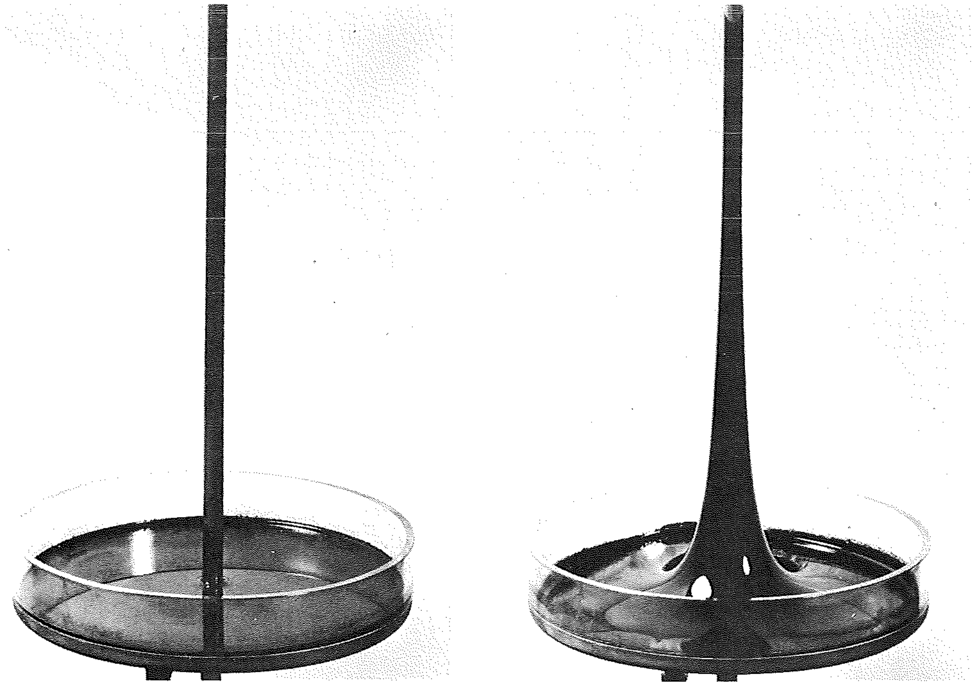

Figure 7. - A dish of ferrofluid surrounding a wire; when current flows as on the right the magnetic field attracts the fluid up the wire. Photo courtesy of R. E. Rosensweig.

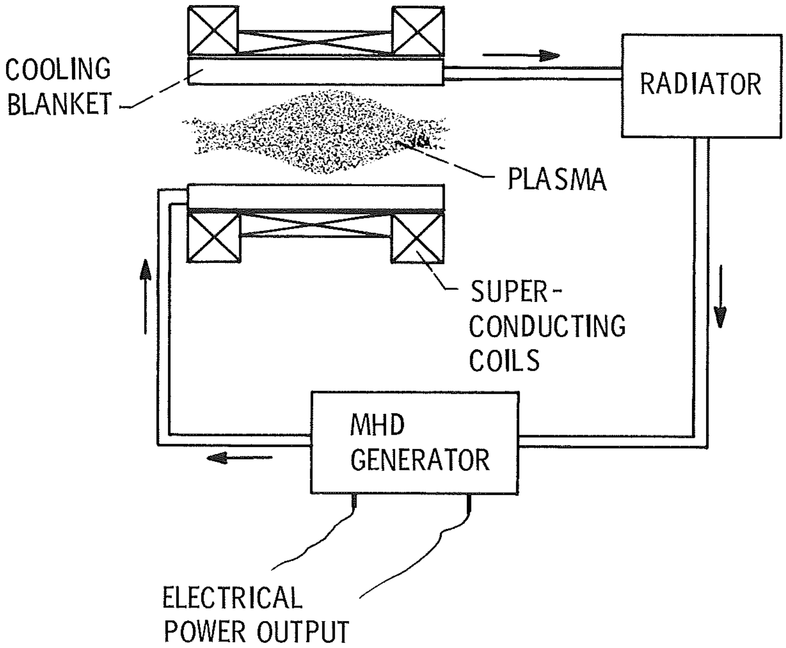

Figure 8. - Schematic of a thermonuclear power system using magnetocaloric cycle.

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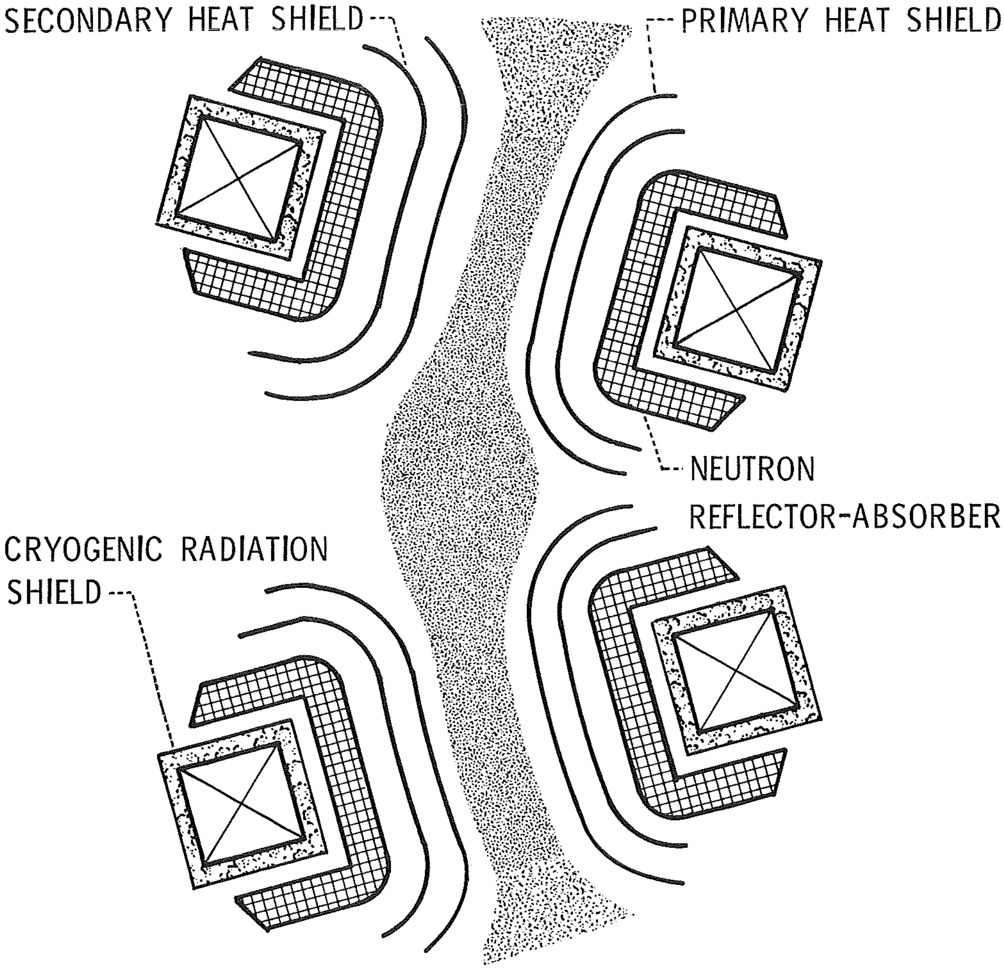

Figure 9. - Sketch of shielding components needed for the superconducting coils in a space fusion system.

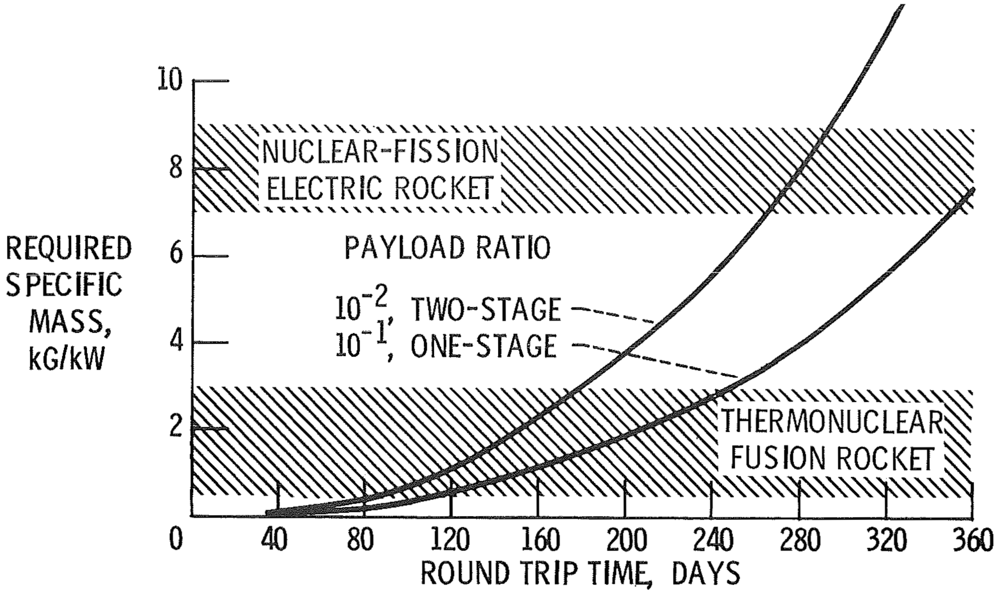

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Figure 10. - Time required for a Mars round trip as affected by propulsion system characteristics.

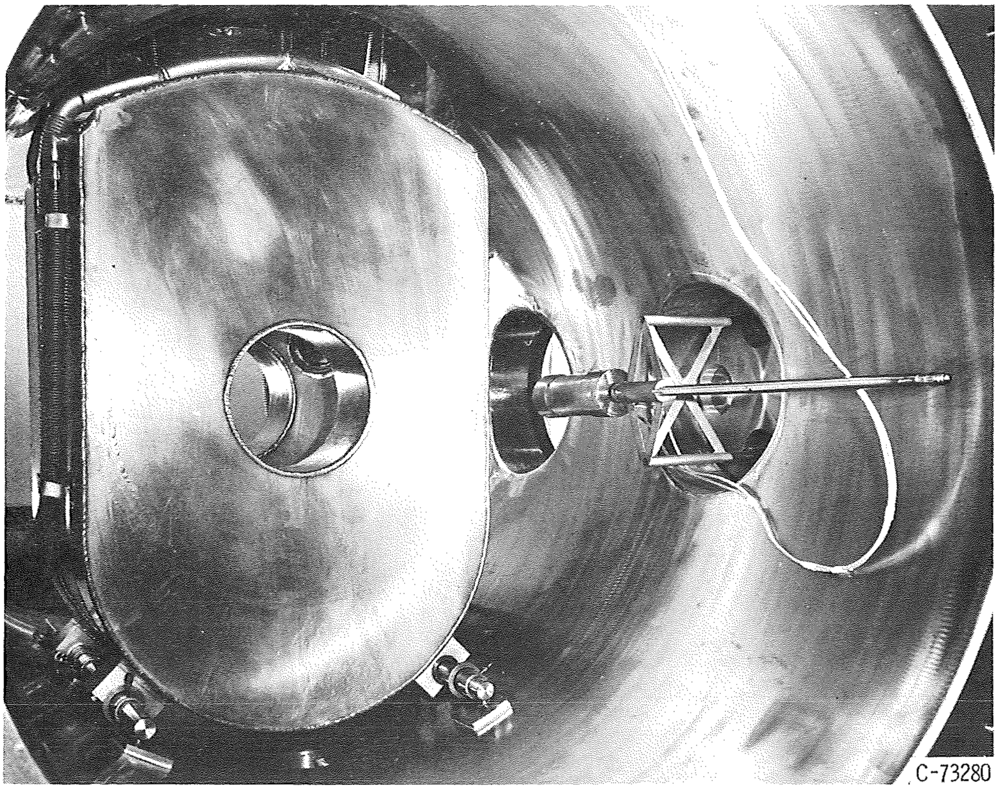

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Figure 11. - Superconducting magnet facility used in plasma research. View of superconducting magnet dewars through open end of vacuum tank.

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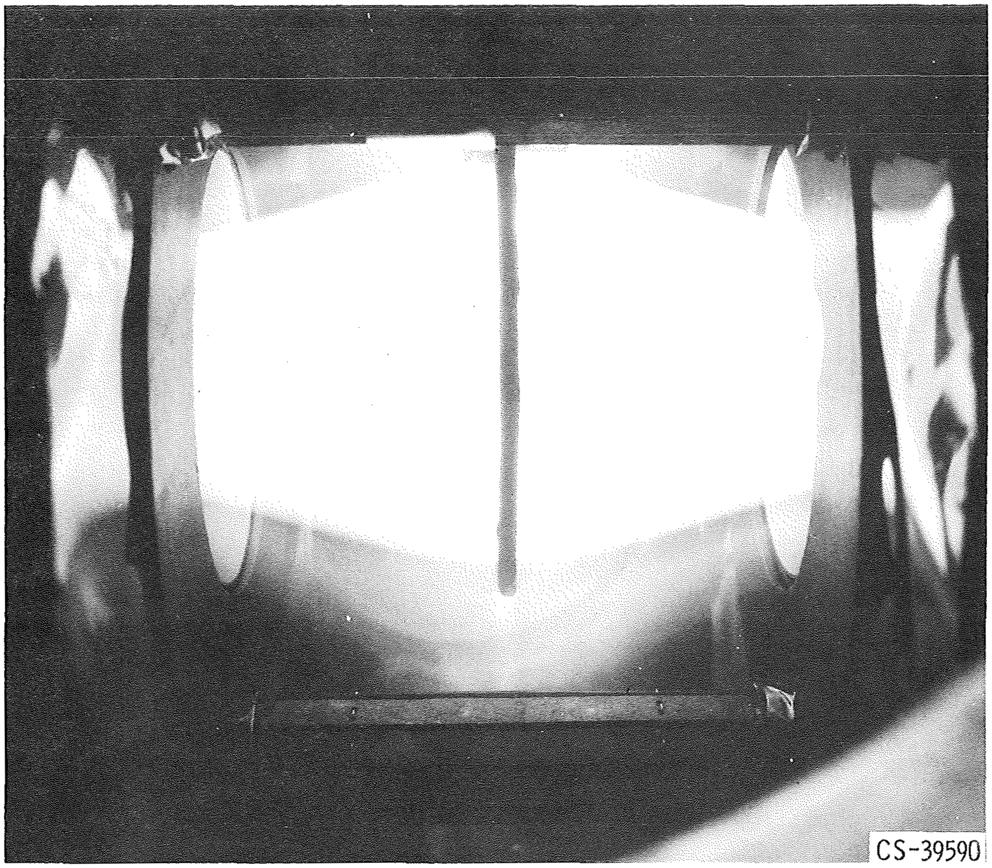

Figure 12. - Modified Penning discharge in superconducting magnetic mirror facility; the anode ring (vertical element in center) operates at high positive potentials.

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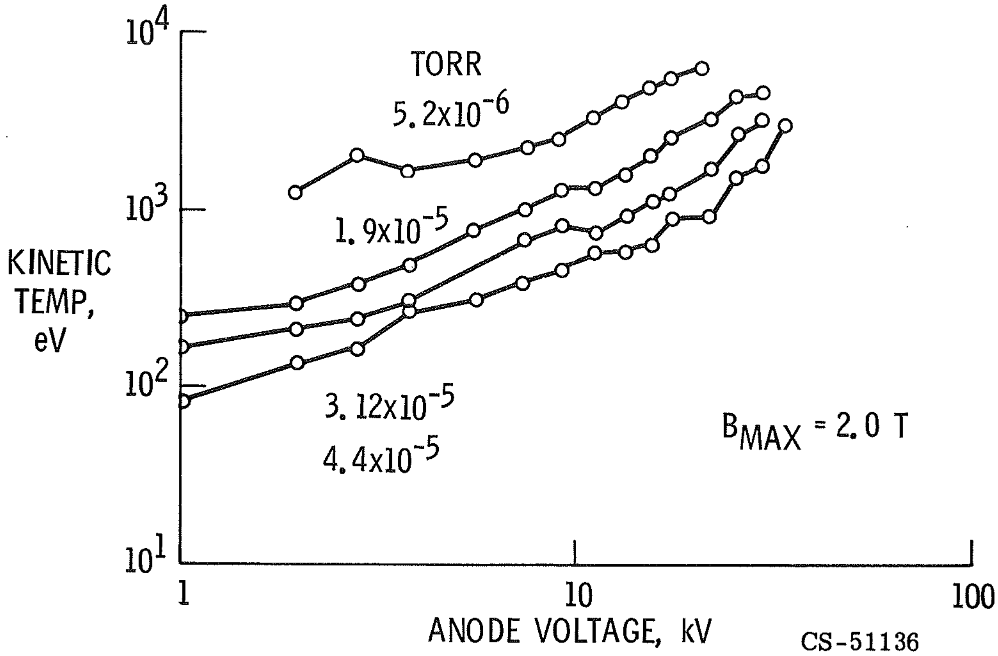

Figure 13. - Deuterium ion kinetic temperatures obtained in modified Penning discharge at various background pressures.

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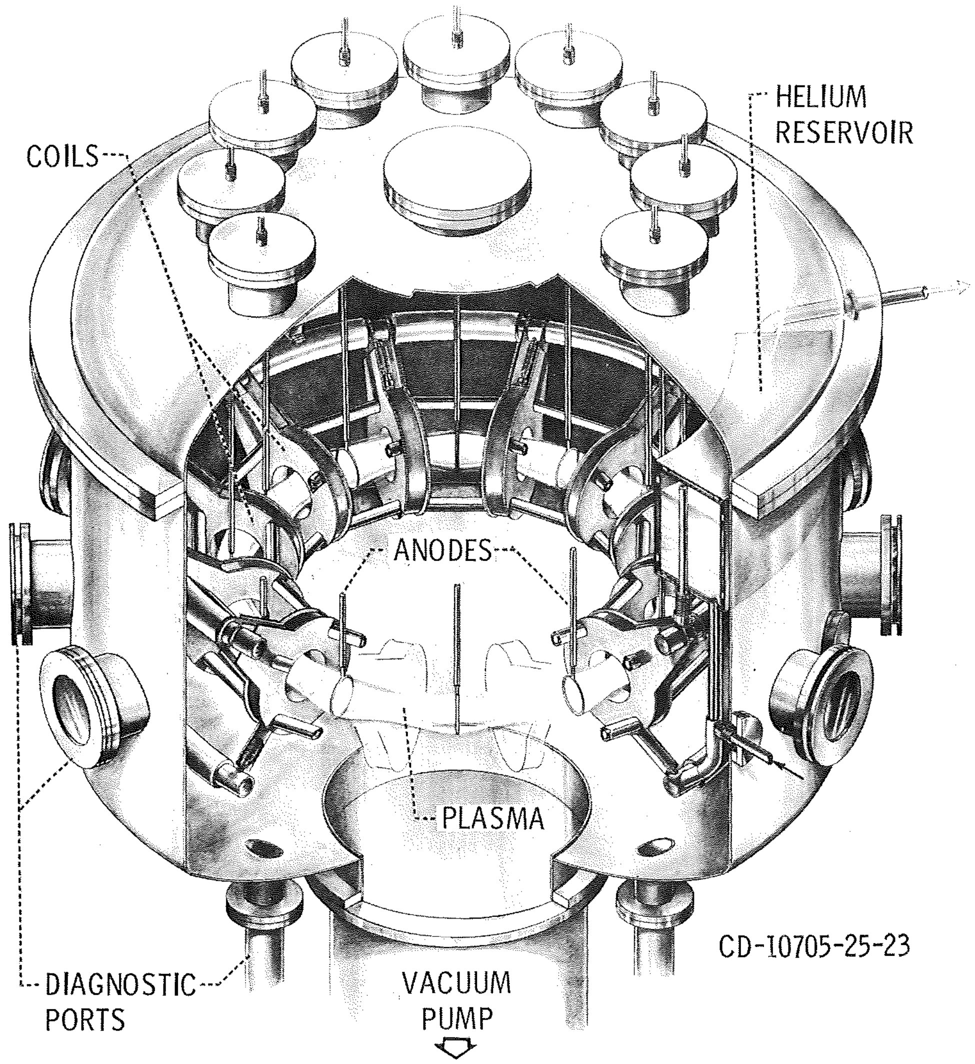

Figure 14. - Cutaway view of proposed bumpy torus facility. Magnetic field, 3 T on coil axes; plasma major diameter, 150 cm, minor diameter, about 15 cm.

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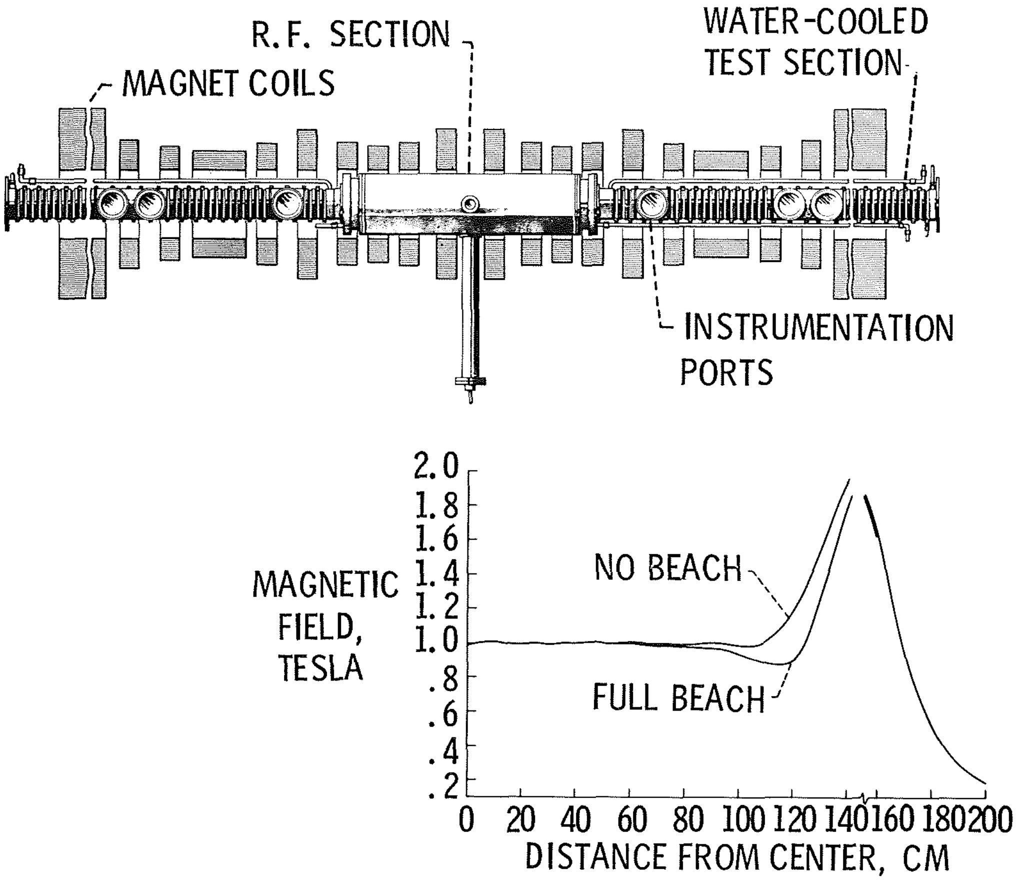

(A) OVERALL VIEW WITH MAGNETIC FIELD SHOWN.

Figure 15. - Experimental apparatus for study of plasma heating by ion cyclotron resonance.

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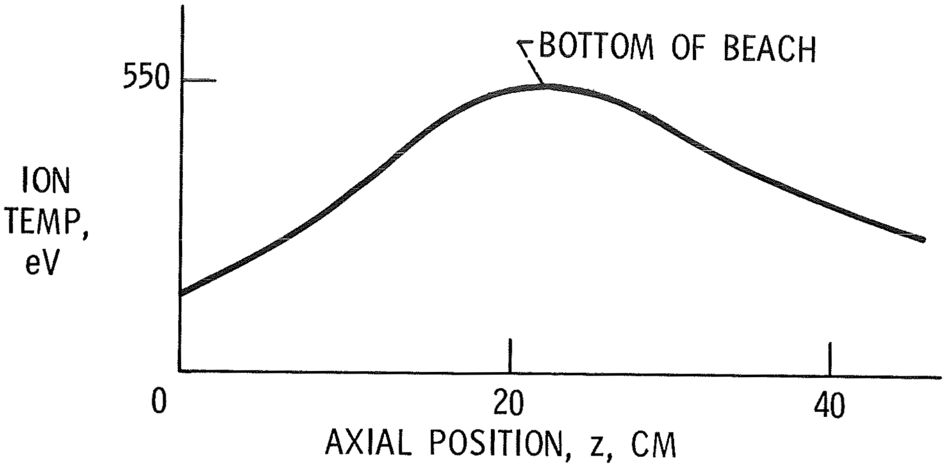

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Figure 16. - Ion temperatures resulting from ion cyclotron resonance heating; measurements in the region of the magnetic beach.

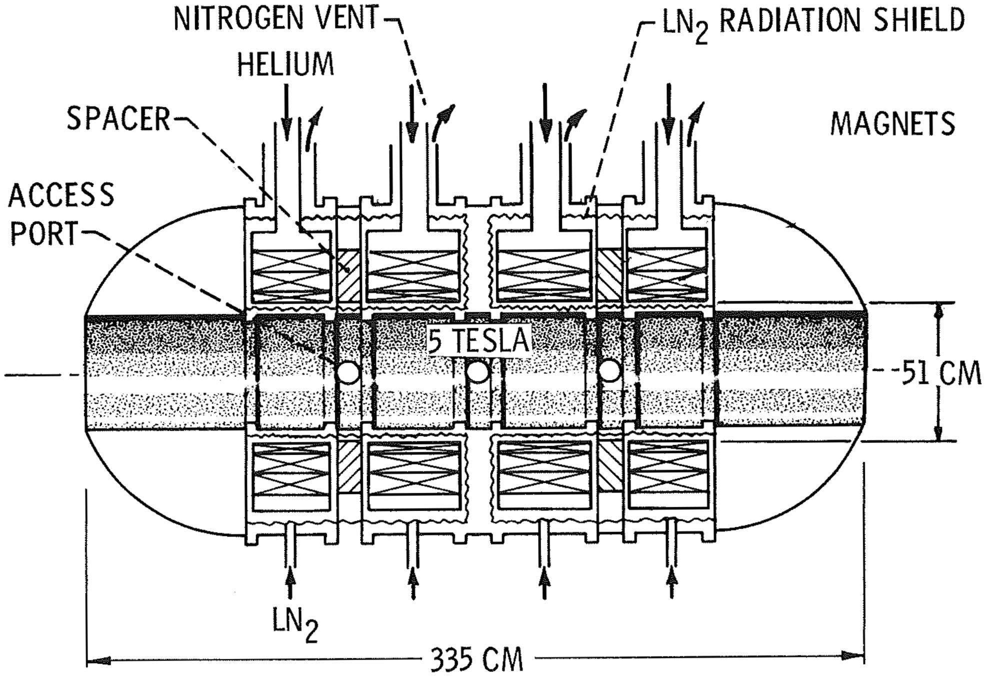

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Figure 17. - Sketch of proposed superconducting magnetic mirror facility.